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Disturbance Distance: quantifying forests' vulnerability to disturbance under current and future conditions

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Abstract

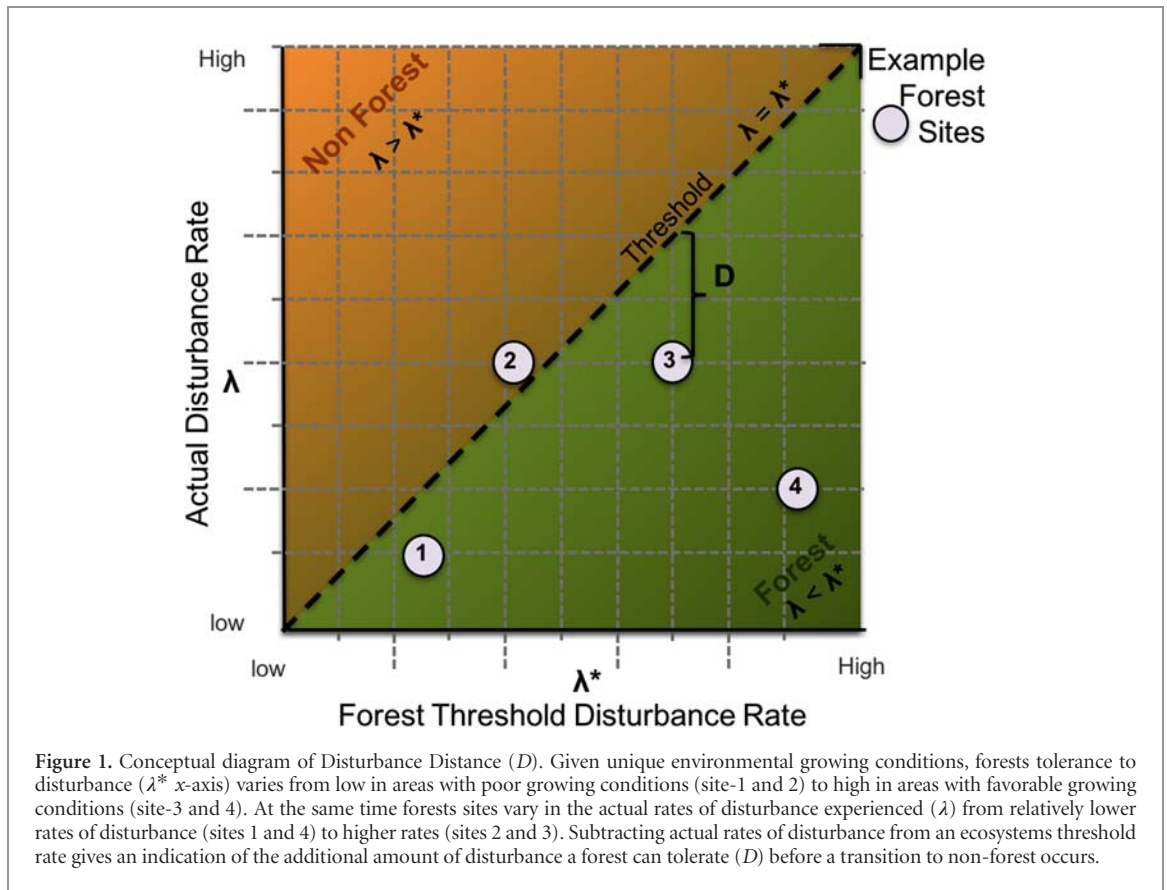
Disturbances, both natural and anthropogenic, are critical determinants of forest structure, function, and distribution. The vulnerability of forests to potential changes in disturbance rates remains largely unknown. Here, we developed a framework for quantifying and mapping the vulnerability of forests to changes in disturbance rates. By comparing recent estimates of observed forest disturbance rates over a sample of contiguous US forests to modeled rates of disturbance resulting in forest loss, a novel index of vulnerability, Disturbance Distance, was produced. Sample results indicate that 20% of current US forestland could be lost if disturbance rates were to double, with southwestern forests showing highest vulnerability. Under a future climate scenario, the majority of US forests showed capabilities of withstanding higher rates of disturbance than under the current climate scenario, which may buffer some impacts of intensified forest disturbance.

While climate attributes such as temperature and precipitation are principal determinants of the distribution of the world's ecosystems (i.e. tundra vs. forestland), natural disturbances such as fire, wind, and other events can also influence the distribution and properties of ecological systems [1]. Within forested ecosystems, disturbance influences forest structure, function and composition, and thus the ecosystem services they provide [2–5]. Recent studies have highlighted changes in natural disturbance regimes compared to historic norms and the potential for further alterations in disturbance regimes from future climate change on a scale unprecedented in historic records [6–13]. These studies lead to a key question: What levels of disturbance can forests tolerate before they face critical alterations in structure and function and how might their sensitivity to disturbance change under future climate?

While field studies that characterize and/or simulate the impact of disturbance continue to be vital to our understanding of changing disturbance impacts to forested ecosystems, it is difficult and often impractical

to extend these studies to continental and centennial scales [14, 15]. Thus, process-based prognostic models that can simulate events over larger areas and temporal scales have been used to advance our understanding of regional to global ecosystem dynamics. Previous studies have explored a range of topics such as the modification of global vegetation in a world without fire, to the potential impacts of large-scale deforestation in Tropical and Boreal regions, to the dependence of future climate mitigation strategies on the future rate of natural disturbance rates [1, 16–18].

Given the critical roles disturbance plays in shaping forest structure, function, and dynamics, we propose a framework to assess ecosystem vulnerability to disturbances. Specifically, we sought to address the following questions: (1) What is the maximum rate of disturbance for which current forests can be maintained across the US?; (2) How close are current forests to a fundamental shift in ecosystem structure?; and, (3) How may forest



ecosystem sensitivity to disturbance change under a potential future climate change scenario?

Forest vulnerability to disturbance was determined by developing a simple and flexible framework. First, ecosystem responses to disturbance are evaluated under representative climatic and environmental conditions to determine threshold rates of disturbance (λ^*), the rates that lead to fundamental alterations of vegetation structure (i.e. transition from forest to non-forest based on criteria of plant structure, composition and biomass). While forests with favorable growing conditions recover faster and can thus tolerate higher disturbance, the same level of disturbance on a site with poor growing conditions can be enough to tip the land into a different ecosystem type [19]. Next, estimates of actual forest disturbance rates (λ) are acquired over forested regions. Comparing these observed rates of disturbance to the estimated threshold rates provide estimates of how much additional disturbance an ecosystem may tolerate before a transition threshold is reached, herein termed Disturbance Distance (equation (1))

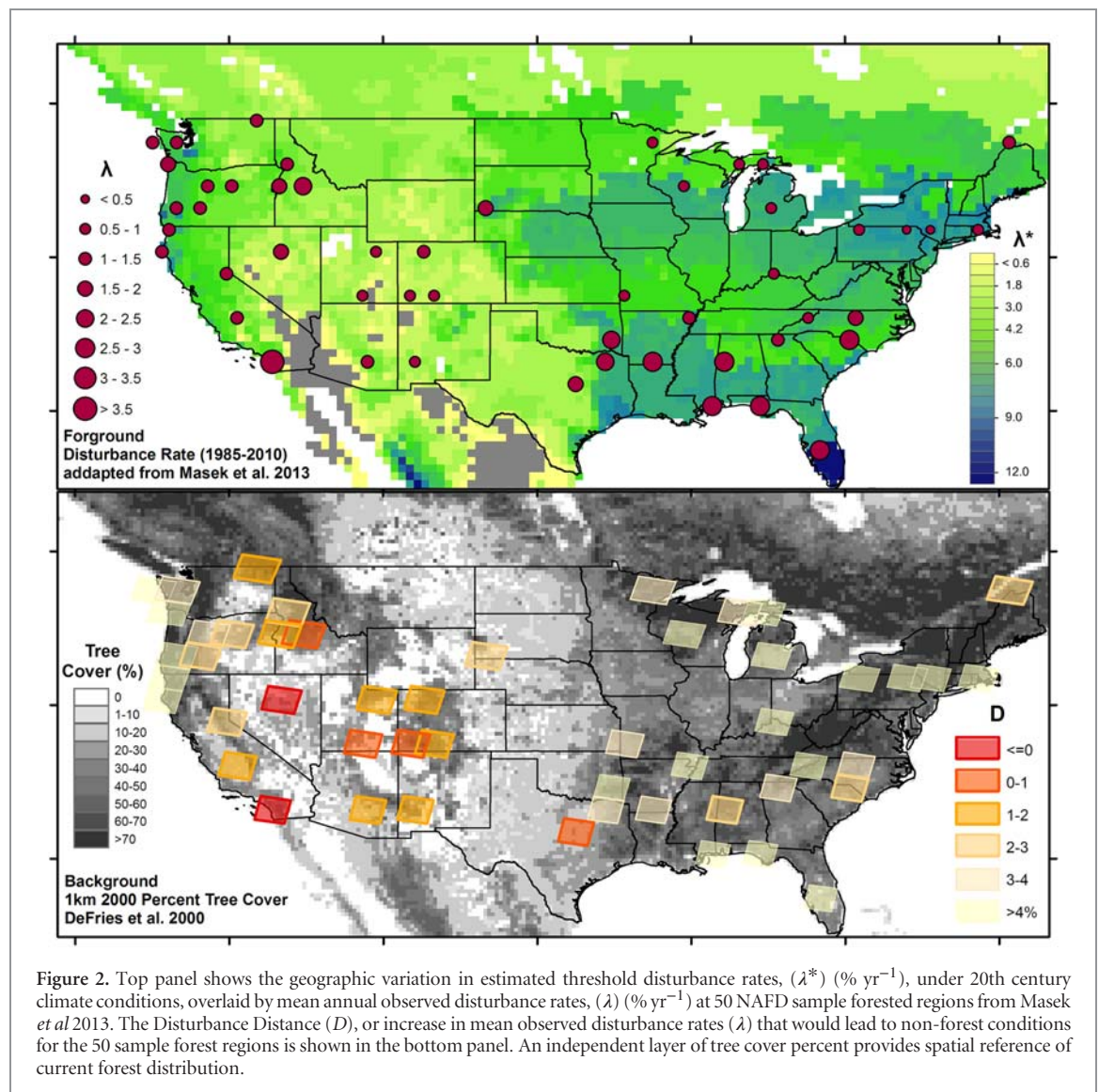
$$D = \lambda^* - \lambda. \quad (1)$$

A region's Disturbance Distance, D , gives insight into its vulnerability to potential increases in disturbance intensity (figure 1).

In this report, threshold disturbance rates (λ^*) for which forest conditions could be maintained across the contiguous US were estimated by simulating potential vegetation growth and dynamics under

varying disturbance rate scenarios in an advanced mechanistic and prognostic ecosystem model [20] (see methods supplement available at stacks.iop.org/ERL/12/114015/mmedia). Following previous studies [3, 21] the forest threshold definition used here, required the maintenance of forest plant functional types and an above ground standing stock of natural cover equivalent to 2 kgC m^{-2} or greater. While the individual-based mechanistic model was chosen in part due to its capabilities to incorporate sub-models of disturbance that may allow future studies of disturbance interactions and feedbacks [3, 22], to isolate the average disturbance rate leading to non-forest conditions, all sub-models were turned off and annual disturbance rates were held constant in time and space within each model run. The modeled-based results of this simplified disturbance case study indicate that forests in southeastern US can maintain the highest rates of disturbance before non-forest conditions are reached, while southwestern forests were estimated to have the lowest disturbance rate thresholds (figure 2).

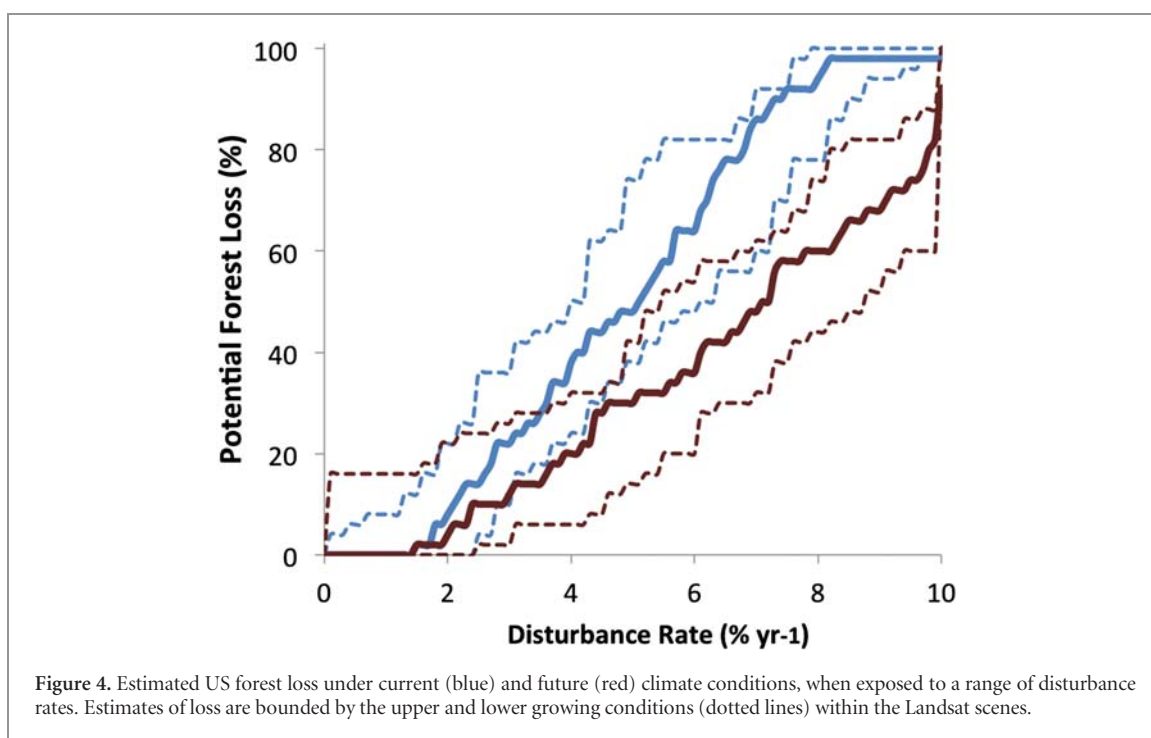
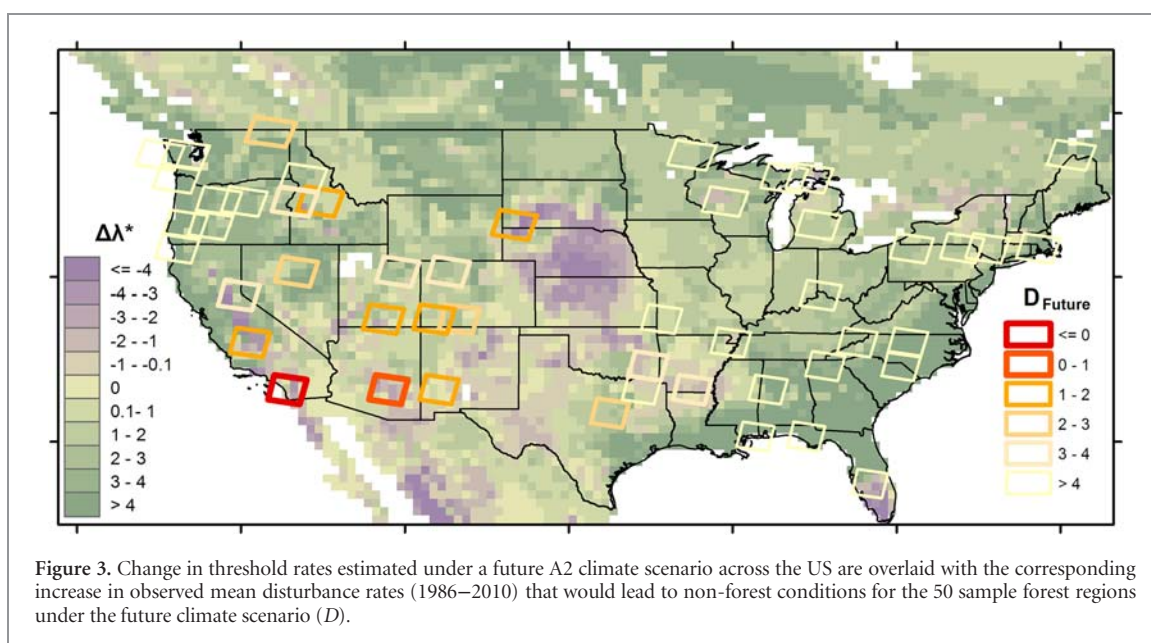
To estimate how far current forests may be from a transition to non-forest, threshold rates of disturbance (λ^*) were compared to remotely sensed derived estimates of disturbance over 50 US forested Landsat scenes representative of major forest types [23]. The observed average annual disturbance rates (λ), measured as the percent of live forest cover loss persisting 2 or more years between 1986–2010, ranged from $0.4\% - 3.8\% \text{ yr}^{-1}$ with a national average of $1.4\% \text{ yr}^{-1}$ (figure 2, figure S1). Over these same forested



scenes, under 20th century climate conditions, average threshold rates of disturbance (λ^*) ranged from $\sim 1.5\% - 12\% \text{ yr}^{-1}$ (figure 2). In general, Disturbance Distances were estimated to be much smaller across western forests (west of 100 W) with nearly half the western sites estimated to transition to non-forest if an additional 2% of forest area was disturbed annually, while only one eastern forested site showed this same vulnerability (figure 2, figure S2). In a scenario where current disturbance rates double, and assuming the 50 Landsat scenes are representative of US forests, $\sim 20\%$ or 51 million hectares of forests would be exposed to disturbance-induced transitions to non-forest ecosystems (figure 4, figure S3), while the timing of transition will vary in part due to rate of disturbance and recovery.

Vegetation growth and response to disturbance will change under future climate conditions. To evaluate how forests' sensitivity to disturbance may change in the future, the threshold rates of disturbance were estimated under a representative future climatology from the North American Regional Climate Change Assessment Program (NARCCAP) which is based off

the IPCC A2 emissions scenario [24] (see methods supplement). The estimated thresholds rates under the future climate scenario, were again compared to the remotely observed disturbance rates, to estimate forests' Disturbance Distance under a future climate scenario. The resulting Disturbance Distances (D) were higher over the majority of sites (figure 3), suggesting an overall decrease in vulnerability to increased disturbance rates under this specific future scenario. Only 15% of all sampled forest scenes showed a decline in tolerance to disturbance, and the share of forests susceptible to loss if current disturbance rates were to double was reduced by $\sim 50\%$ (figure 4, figure S4). The southern California site stands out as an extremely vulnerable outlier, as the disturbance distance was slightly negative under 20th century climate and decreased further in the future scenario. Conversely, northwestern forests showed the largest potential to decrease vulnerability under the future climate scenario. Overall, we estimated the majority of US forests will be able to tolerate higher rates of disturbance under a future climate scenario than under a contemporary climate (figure 4).



Projected changes in future climate and disturbance regimes have heightened the need for continued research on forest disturbance and ecosystem response monitoring and modeling capabilities. Here we used an advanced ecosystem model to estimate a novel metric, disturbance rate threshold, which measured the highest rates of disturbance that can be tolerated before non forest conditions persist across the diverse climatic and edaphic gradients found within the continental US. Comparing this metric to measured rates of forest disturbance across the US quantified patterns of forest vulnerability to altered rates of disturbance. This study thus provides a preliminary baseline and flexible framework that can be applied to additional

regions and adapted to specific research objectives. Our case study focused on transitions to non forest, but before non forest conditions are met changes in disturbance rates are likely to cause other important structural and functional ecological modifications such as changes in species composition, carbon sequestration potential, basal area, and forest height [14, 15, 19, 25–27]. This framework could provide guidance on management intervention to ease the transition to new and better adapted forest states [28], and may identify areas that have not been historically defined as forests, but have the potential to sustain them if disturbances such as grazing and/or fire were suppressed below critical threshold rates [1, 29].

This case study highlights the differences in forest vulnerability to altered disturbance rates across the US. Results show most forested regions can withstand higher disturbance rates than the average rates detected by remote sensing and that most US forests will be able to withstand higher rates of disturbance in the future. Many complex and non-linear interactions between climate, soils and atmospheric CO₂ concentrations effect vegetation growth, mortality and competition [11, 30–32]. Thus as climate and edaphic conditions vary across the US so do the variance in the magnitude and direction of change in vulnerability to disturbance. In particular, this study suggests some forested areas, particularly water-limited areas of the western US, could become more vulnerable to increases in disturbance rates under an IPCC A2 climate scenario. This finding is aligned with several recent papers documenting increased mortality in western forests arising from decreased water availability driven by warmer and drier conditions [9, 13, 33]. The finding that the majority of the contiguous US forests may become less vulnerable to disturbance under a future climate scenario coincides with previous studies that have shown enhanced productivity stimulated by increases in CO₂ and temperature [34–36], although sustained enhancement of vegetation to CO₂ has been questioned [37–39]. Our study does not attempt to project what future disturbance rates will be and it is very conceivable that disturbance rates (i.e. more frequent fires, intense storms and pest and pathogen outbreaks) could increase at levels that limit any projected gains in recovery potential from climate change [6, 10–12, 40]. Currently beyond the scope of our present study, we suggest incorporating more disturbance and climate change scenarios into the modeling framework, to better quantify the range of vegetation response to altered disturbance and encourage continued model inter-comparisons to test vulnerability under a range of ecological assumptions [41–45]. More detailed investigations of ecosystem health and impact, adaptation and vulnerability studies (IAV) are needed.

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References

- [1] Bond W J, Ian Woodward F and Midgley G F 2005 The global distribution of ecosystems in a world without fire *New. Phytol.* **165** 525–38
- [2] Frolking S, Palace M W, Clark D B, Chambers J Q, Shugart H H and Hurtt G C 2009 Forest disturbance and recovery: a general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure *J. Geophys. Res. Biogeosci.* **114** G00E02
- [3] Hurtt G C, Pacala S W, Moorcroft P R, Caspersen J, Shevliakova E, Houghton R A and Moore B 2002 Projecting the future of the US carbon sink *Proc. Natl Acad. Sci.* **99** 1389–94
- [4] Lorimer C G and White A S 2003 Scale and frequency of natural disturbances in the Northeastern US: implications for early successional forest habitats and regional age distributions *Forest Ecol. Manage.* **185** 41–64
- [5] Oliver C D *et al* 1996 *Forest Stand Dynamics: Updated Edition* (New York: Wiley)
- [6] Dale V H *et al* 2001 Climate change and forest disturbances *BioScience* **51** 723–34
- [7] Kurz W A, Dymond C C, Stinson G, Rampley G J, Neilson E T, Carroll A L, Ebata T and Safranyik L 2008 Mountain pine beetle and forest carbon feedback to climate change *Nature* **452** 987–90
- [8] Zeng H, Chambers J Q, Negrón-Juárez R I, Hurtt G C, Baker D B and Powell M D 2009 Impacts of tropical cyclones on US forest tree mortality and carbon flux from 1851 to 2000 *Proc. Natl Acad. Sci.* **106** 7888–92
- [9] Allen C D *et al* 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests *Forest Ecol. Manage.* **259** 660–84
- [10] Bentz B J, Régnière J, Fettig C J, Matthew Hansen E, Hayes J L, Hicke J A, Kelsey R G, Negrón J F and Seybold S J 2010 Climate change and bark beetles of the western united states and canada: direct and indirect effects *BioScience* **60** 602–13
- [11] Seidl R *et al* 2017 Forest disturbances under climate change *Nat. Clim. Change* **7** 395–402
- [12] Trumbore S, Brando P and Hartmann H 2015 Forest health and global change *Science* **349** 814–8
- [13] Cohen W B, Yang Z, Stehman S V, Schroeder T A, Bell D M, Masek J G, Huang C and Meigs G W 2016 Forest disturbance across the conterminous united states from 1985–2012: the emerging dominance of forest decline *Forest Ecol. Manage.* **360** 242–52
- [14] Rogers P 1996 Disturbance ecology and forest management: a review of the literature *Gen. Tech. Rep. INT-GTR-336*, US Department of Agriculture, Intermountain Research Station, Ogden, Utah 16 p
- [15] Reyer C P O *et al* 2015 Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges *J. Ecol.* **103** 5–15
- [16] Shukla J *et al* 1990 Amazon deforestation and climate change *Science (Washington)* **247** 1322–5
- [17] Bonan G B, Pollard D and Thompson S L 1992 Effects of boreal forest vegetation on global climate *Nature* **359** 716–8
- [18] Yannik Le P *et al* 2013 Sensitivity of climate mitigation strategies to natural disturbances *Environ. Res. Lett.* **8** 015018
- [19] Turner M G, Romme W H, Gardner R H, O'Neill R V and Kratz T K 1993 A revised concept of landscape equilibrium: disturbance and stability on scaled landscapes *Landscape Ecol.* **8** 213–27
- [20] Moorcroft P R, Hurtt G C and Pacala S W 2001 A method for scaling vegetation dynamics: the ecosystem demography model (ED) *Ecol. Monogr.* **71** 557–86

- [21] Hurtt G C *et al* 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Clim. Change* **109** 117
- [22] Fisk J P, Hurtt G C, Chambers J Q, Zeng H, Dolan K A and Negrón-Juárez R I 2013 The impacts of tropical cyclones on the net carbon balance of eastern US forests 1851–2000 *Environ. Res. Lett.* **8** 045017
- [23] Masek J G, Goward S N, Kennedy R E, Cohen W B, Moisen G G, Schleeweis K and Huang C 2013 United states forest disturbance trends observed using landsat time series *Ecosystems* **16** 1087–104
- [24] Mearns L O, Gutowski W, Jones R, Leung R, McGinnis S, Nunes A and Qian Y 2009 A regional climate change assessment program for North America *Eos. Trans. Am. Geophys. Un.* **90** 311–1
- [25] McDowell N G *et al* 2015 Global satellite monitoring of climate-induced vegetation disturbances *Trends Plant Sci.* **20** 114–23
- [26] Kasischke E S, Amiro B D, Barger N N, French N H F, Goetz S J, Grosse G, Harmon M E, Hicke J A, Liu S and Masek J G 2013 Impacts of disturbance on the terrestrial carbon budget of North America *J. Geophys. Res. Biogeosci.* **118** 303–16
- [27] Flanagan S A, Hurtt G C, Fisk J P, Sahajpal R, Hansen M C, Dolan K A, Sullivan J H and Zhao M 2016 Potential vegetation and carbon redistribution in Northern North America from climate change *Climate* **4** 2
- [28] Millar C I and Stephenson N L 2015 Temperate forest health in an era of emerging megadisturbance *Science* **349** 823–6
- [29] Briggs J M, Knapp A K, Blair J M, LHeisler J, Hoch G A, Lett M S and McCarron J K 2005 An ecosystem in transition: causes and consequences of the conversion of mesic grassland to shrubland *BioScience* **55** 243–54
- [30] Melillo J M, Callaghan T V, Woodward F I, Salati E and Sinha S 1990 Effects on ecosystems Climate Change: The IPCC Scientific Assessment pages 283–310
- [31] Ghannoum O and Way D A 2011 On the role of ecological adaptation and geographic distribution in the response of trees to climate change *Tree Physiol.* **31** 1273–6
- [32] Nunes L, Gower S T, Peckham S D, Magalhães M, Lopes D and Rego F C 2014 Estimation of productivity in pine and oak forests in northern Portugal using Biome-BGC *Forest Int. J. Forest Res.* **88** 200–12
- [33] Breshears D D *et al* 2005 Regional vegetation die-off in response to global-change-type drought *Proc. Natl Acad. Sci. USA* **102** 15144–8
- [34] Norby R J *et al* 2005 Forest response to elevated CO₂ is conserved across a broad range of productivity *Proc. Natl Acad. Sci. USA* **102** 18052–6
- [35] Idso S B and Kimball B A 1993 Tree growth in carbon dioxide enriched air and its implications for global carbon cycling and maximum levels of atmospheric CO₂ *Glob. Biogeochem. Cycles* **7** 537–55
- [36] Higgins S I and Scheiter S 2012 Atmospheric CO₂ forces abrupt vegetation shifts locally, but not globally *Nature* **488** 209–12
- [37] Reich P B, Hobbie S E, Lee T, Ellsworth D S, West J B, Tilman D, Knops J M H, Naeem S and Trost J 2006 Nitrogen limitation constrains sustainability of ecosystem response to CO₂ *Nature* **440** 922
- [38] Oren R *et al* 2001 Soil fertility limits carbon sequestration by forest ecosystems in a CO₂-enriched atmosphere *Nature* **411** 469
- [39] Warren J M, Norby R J and Wullschlegel S D 2011 Elevated CO₂ enhances leaf senescence during extreme drought in a temperate forest *Tree Physiol.* **31** 117–30
- [40] Liu Z and Wimberly M C 2016 Direct and indirect effects of climate change on projected future fire regimes in the western united states *Sci. Total Environ.* **542** 65–75
- [41] Wei Y *et al* 2014 The north american carbon program multi-scale synthesis and terrestrial model intercomparison project—Part 2: environmental driver data *Geosci. Model Dev.* **7** 2875–93
- [42] Sitch S *et al* 2008 Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five dynamic global vegetation models (dgvms) *Glob. Change Biol.* **14** 2015–39
- [43] Bond-Lamberty B, Fisk J P, Holm J A, Bailey V, Bohrer G and Gough C M 2015 Moderate forest disturbance as a stringent test for gap and big-leaf models *Biogeosciences* **12** 513–26
- [44] Dietze M C *et al* 2014 A quantitative assessment of a terrestrial biosphere model's data needs across north american biomes *J. Geophys. Res. Biogeosci.* **119** 286–300
- [45] McDowell N G, Beerling D J, Breshears D D, Fisher R A, Raffa K F and Stitt M 2011 The interdependence of mechanisms underlying climate-driven vegetation mortality *Trends Ecol Evol.* **26** 523–32
- [46] Hurtt G C *et al* 1998 Terrestrial models and global change: challenges for the future *Glob. Change Biol.* **4** 581–90
- [47] Batjes N H 2012 Isric-wise derived soil properties on a 5 by 5 arc-minutes global grid *Technical Report* ISRIC-World Soil Information
- [48] Dolan K A, Hurtt G C, Chambers J Q, Dubayah R O, Frolking S and Masek J G 2011 Using icesat's geoscience laser altimeter system (glas) to assess large-scale forest disturbance caused by hurricane katrina *Remote Sens. Environ.* **115** 86–96
- [49] Hurtt G C, Dubayah R, Drake J, Moorcroft P R, Pacala S W, Blair J B and Fearon M G 2004 Beyond potential vegetation: combining lidar data and a height-structured model for carbon studies *Ecol. Appl.* **14** 873–83
- [50] Thomas R Q, Hurtt G C, Dubayah R and Schilz M H 2008 Using lidar data and a height-structured ecosystem model to estimate forest carbon stocks and fluxes over mountainous terrain *Can. J. Remote Sens.* **34** S351–63
- [51] Hurtt G C, Fisk J, Thomas R Q, Dubayah R, Moorcroft P R and Shugart H H 2010 Linking models and data on vegetation structure *J. Geophys. Res. Biogeosci.* **115** G00E10
- [52] Fisk J 2015 Net effects of disturbance: spatial, temporal, and societal dimensions of forest disturbance and recovery on terrestrial carbon balance *PhD Dissertation* (University of New Hampshire)
- [53] Goward S N *et al* 2008 Forest disturbance and north american carbon flux *Eos. Trans. Am. Geophys. Un.* **89** 105–6
- [54] Huang C *et al* 2009 Development of time series stacks of landsat images for reconstructing forest disturbance history *Int. J. Digital Earth* **2** 195–218
- [55] Huang C, Goward S N, Masek J G, Thomas N, Zhu Z and Vogelmann J E 2010 An automated approach for reconstructing recent forest disturbance history using dense landsat time series stacks *Remote Sens. Environ.* **114** 183–98
- [56] Thomas N E, Huang C, Goward S N, Powell S, Rishmawi K, Schleeweis K and Hinds A 2011 Validation of north american forest disturbance dynamics derived from landsat time series stacks *Remote Sens. Environ.* **115** 19–32
- [57] Fisher J I, Hurtt G C, Quinn Thomas R and Chambers J Q 2008 Clustered disturbances lead to bias in large-scale estimates based on forest sample plots *Ecol. Lett.* **11** 554–63
- [58] Schleeweis K, Goward S N, Huang C, Masek J G, Moisen G, Kennedy R E and Thomas N E 2013 Regional dynamics of forest canopy change and underlying causal processes in the contiguous US *J. Geophys. Res. Biogeosci.* **118** 1035–53
- [59] Chambers J Q, Negrón-Juárez R I, Marra D M, Di Vittorio A, Tews J, Roberts D, Ribeiro G H P M, Trumbore S E and Higuchi N 2013 The steady-state mosaic of disturbance and succession across an old-growth central amazon forest landscape *Proc. Natl Acad. Sci.* **110** 3949–54